1945

A technique for making torsion balance surveys of inundated areas

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A TECHNIQUE FOR MAKING TORSION BALANCE SURVEYS OF INUNDATED AREAS

BY

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THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

ENGINEER OF MINES

Rolla, Missouri

1945

Approved by J. Donald Forrester

ACKNOWLEDGMENTS

The writer wishes to thank The Salt Dome Oil Corporation for permission to publish most of the factual data here included. He is also grateful to Dean Curtis Wilson and Professon J. D. Forrester for encouragement and valuable suggestions; to Herbert Von Eiff and Clarence Aschbacher for assistance in the drafting of maps and diagrams; and expecially to Ivan J. Fenn, without whose able assistance this thesis would not have been possible. And, finally, he is indebted to Dr. E. E. Rosaire, who read the manuscript and made valuable criticism and suggestions.

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A TECHNIQUE FOR MAKING TORSION BALANCE SURVEYS OF INUNDATED AREAS

INTRODUCTION:

The need for a technique for making torsion balance surveys of inundated areas was brought to the writer's attention during the years of 1927 to 1933, while employed by The Sinclair Exploration Company to prospect for oil in Austria, Hungary and North and Northwest Germany. At that time, the company was using ten torsion balances, supplementing the work with magnetometer surveys and refraction seismograph detail. During part of this period an elementary and relatively insensative gravimeter was used. Some reflection seismograph work was also done during the last year of operations. During the course of surveying in North and Northwest Germany, many inundated areas were encountered on which it was impossible to obtain geophysical data. Adjacent to one of these areas, the Zwischaner Meer, the direction and intensity of the gravity measurements suggested that a salt dome type of structure might exist within the inundated area.

No method for making geophysical surveys of such inundated areas was then known in Germany. While some measurements of gravity had been made under water by using a pendulum in a submarine[1], such a procedure was not applicable to the relatively shallow bodies of water in which we then were interested. Therefore, it was decided that, if a practical method of making torsion balance surveys of water covered areas could be developed, such a technique would add considerably to the territory available for oil exploration.

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1. Ambronn, Richard, Elements of Geophysics, p. 15.

Experiments were begun in the Zwischaner Meer in the Province of Oldenburg, Germany, in 1930. At the close of 1932 and the beginning of 1933, these experiments were beginning to show results. However, in the spring of 1933 the political upheaval in Germany indicated that operations by foreign capital would be short-lived, and, therefore, it was decided that exploratory work would be abandoned. The experiments were then, of necessity, discontinued.

At this same time, the writer severed his connection with The Sinclair Exploration Company, and, with Dr. F. J. G. Neuman and Dr. W. R. Haubold, two German geophysicists who also were interested in the same problem, moved to Houston, Texas, where the experiments were continued. The decision to move to Houston was made because the hydrographic maps of the Gulf Coastal area of Texas and Louisiana revealed that there were numerous large inundated areas ideal for these experiments and available for exploration if they proved successful.

By the close of 1933, an apparatus had been developed which would hold a torsion balance rigid enough for a reading to be taken over water, and, in the spring of 1934, an actual torsion balance survey of an inundated area was inaugurated. A number of surveys since have been made, and these have proven, by both the seismograph and the drill, to compare well in accuracy with torsion balance surveys of adjacent land areas.

The technique, as now developed, is limited to water with a depth of 50 feet or less, and to areas which have a relatively firm bottom. However, the method, as now developed, opens vast areas to torsion balance exploration, and improvements which will extend the range eventually may be developed.

EXPERIMENTAL WORK

Preliminary Considerations:

There were three possible solutions to the problem of making gravity surveys of inundated areas. One was to revise the gravity measuring instruments, the torsion balance, the gravimeter or the pendulum, so that they would not be affected by the movement characteristic of a boat or raft floating upon the water. Another would be to invent a new means of measuring gravity which would not be affected by this movement. And, finally, there was the possibility of developing a rigid base on which standard equipment could be used.

The last solution, by far the simplest, had the added advantage that the same instrument could be used either on land or water without modification, whereupon the data from adjacent land and water surveys could be used together without recalculation or adjustment.

At the time this experimental work was started, the gravimeter, in its then stage of development, did not compare in sensitivity with the torsion balance. In the adjacent land areas, the torsion balance, rather than the pendulum, had been used extensively. In view of these considerations, the logical experimental attack was to build a base for the torsion balance, for the resulting data then could be tied directly to the gravity surveys on the adjacent land.

The torsion balance was invented by Baron Roland Von Eotvos about 1880. The instrument, its theory and application have been adequately described in the literature[2], and no attempt will be made here to cover these phases of the subject.

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2. See Bibliography

Suffice to say that the torsion balance is an instrument which measures the variations in the distortion or warping of the gravitational field. The balance consists of a beam, on the ends of which are masses or weights carried at different levels, the complete unit being suspended by a torsion fiber or wire. On the Z-beam balance, one mass is carried above the beam, the other below it. Another type, sometimes known as the L-beam balance, carries one mass on the beam and the other suspended below it. A third balance, the inclined beam type, has both masses attached to an inclined beam, thus placing the masses on different levels.

If the gravitational field is not uniform, a difference will be present in the direction of gravitational pull on the two weights which will set up a horizontal force componant on the two weights, causing them to rotate around the suspending wire. The resistance of the wire to torsion reacts against the rotating force until the beam comes to rest at a point of equilibrum.

Because the forces which are measured are extremely minute, the instrument must have a very high order of sensitivity and is, therefore, highly susceptable to vibration of every sort. For this reason, it is necessary that the instrument stand upon a very stable base until the beams[3] come to rest. This stability is not difficult to obtain for surveys on land, but it was the first and most difficult problem to be solved in the attempt to explore water covered areas.

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3. The torsion balance in common use has two parallel beams with the hanging masses at opposite ends.

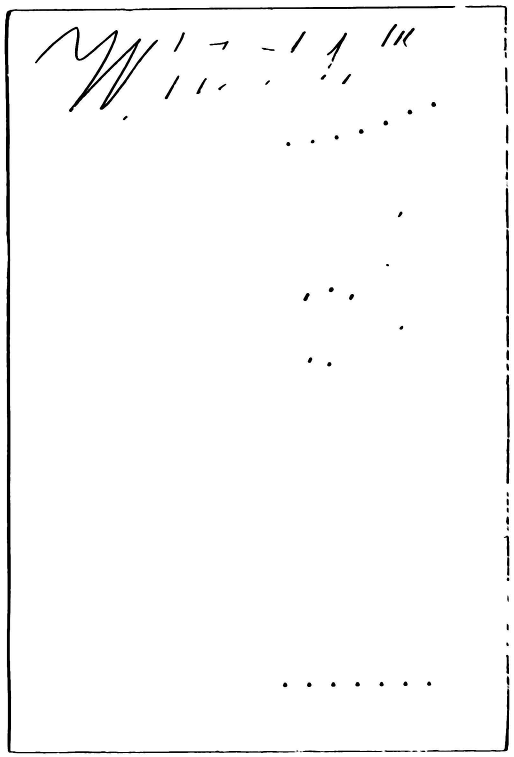

Fig. 1-A

Torsion balance plate of period during which balance did not come to complete rest.

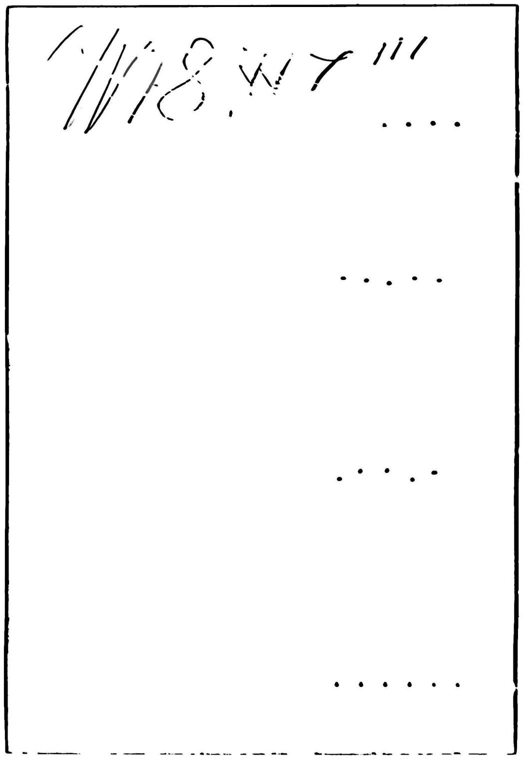

Fig. 1-B

Torsion balance plate of period during which balance came to complete rest.

It was also recognized that any system adopted must be constructed so as not to introduce any variable distortion of the gravitational field. By necessity, some distortion would have to be introduced. If this was kept constant it would not affect the resulting data, as the torsion balance is a relative instrument and measures only changes in the gravitational field.

Experiments with Massive Bases:

The first experiments were conducted on Zwischaner Meer in the Province of Oldenburg, Germany. With the idea in mind that a massive structure was necessary, a piling, about sixty feet long and with an over-all diameter of about ten inches, was driven vertically into a firm clay base under the water, and used as a base. A Z-beam torsion balance, such as was used in all this first experimental work, was placed on top of this piling and an attempt was made to get a reading. The plate, when developed, indicated that the balance had never come to rest, (Fig. 1-A) even though the water had been relatively calm throughout the period in which the reading was taken. Two piling, of the same dimensions as above, then were driven adjacent to each other, with no improvement in results when used as a base. Three were driven, then four, and so on until a cluster of six piling had been formed. With the torsion balance on the center piling of a cluster of six,,an acceptable result was achieved. (Fig 1-B) Readings then were continued on the same cluster in order to discover over what range of wave action this stability would continue. Good results were obtained until the wind reached a velocity of about 18 miles per hour which produced waves approximately three feet high. Under these conditions, so much vibration was transmitted that the instrument did not come to rest. As this was not an unusual wind velocity for this area, it was recognized at this point that the desired stability could not be obtained with wooden piling.

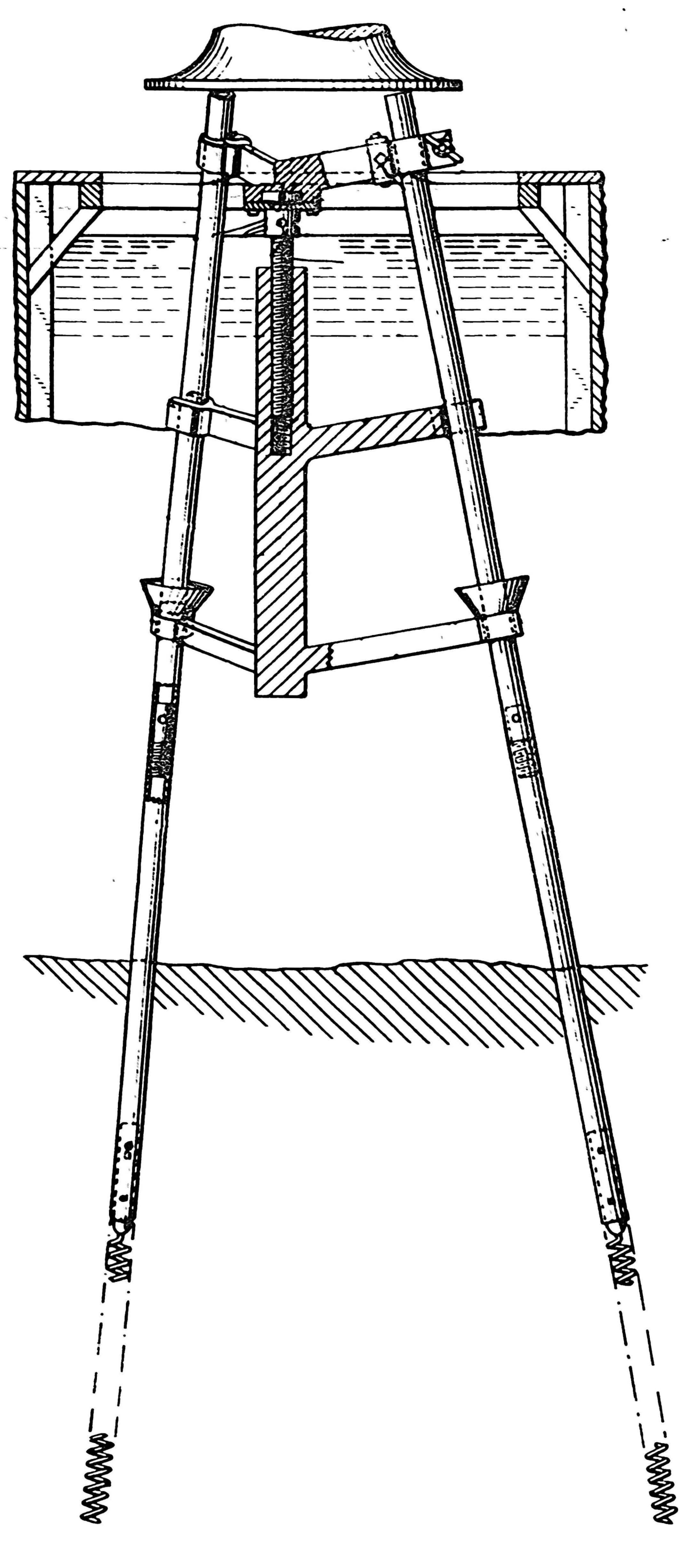

Fig. 2. Drawing showing the construction of the tripod used to support the torsion balance in inundated areas.

Cassions were then substituted for the piling. Quarter inch steel casing, 36 inches in diameter, was selected in two meter lengths, joined togethor and driven vertically through the mud in the lake and approximately two feet into the firm sediments. A small pile driver was used to drive this size casing, and even then it was difficult to drive into the firm bottom. The casing was allowed to extend about four feet above the water. A one inch board platform was placed on the top of the caisson, and the torsion balance was mounted on this. A small tent was placed over the structure to protect the balance against temperature changes due to wind and sun. Readings taken on this structure indicated that the torsion balance did not come to rest even though the water was relatively quiet, indicating that caissons were not the solution for making gravity measurements on water. Further, even if satisfactory data had been obtained by their use, not only was their installation expensive, but also their removal in areas where the needs of navigation were paramount.

After finding that neither piling nor cassions resulted in a stable base for the balance, a new approach was made on the problem. An effort was made to develop, a stable but portable base, one on which the instrument could rest without vibration while the reading was being taken, and which could be used again after having been moved to another location.

With this in mind, a concrete structure or base was built which could be moved from place to place by means of a crane. This base was formed in the shape of a frustum of a four sided pyramid, being about four feet square at the base; about two feet square at the top and from ten to twelve feet tall. The structure was unweildy to handle because of its size, shape and weight, and was difficult to place in a vertical position because of irregulations on the bottom of the lake. Even when finally positioned and the balance placed thereon, leveling was quite difficult.

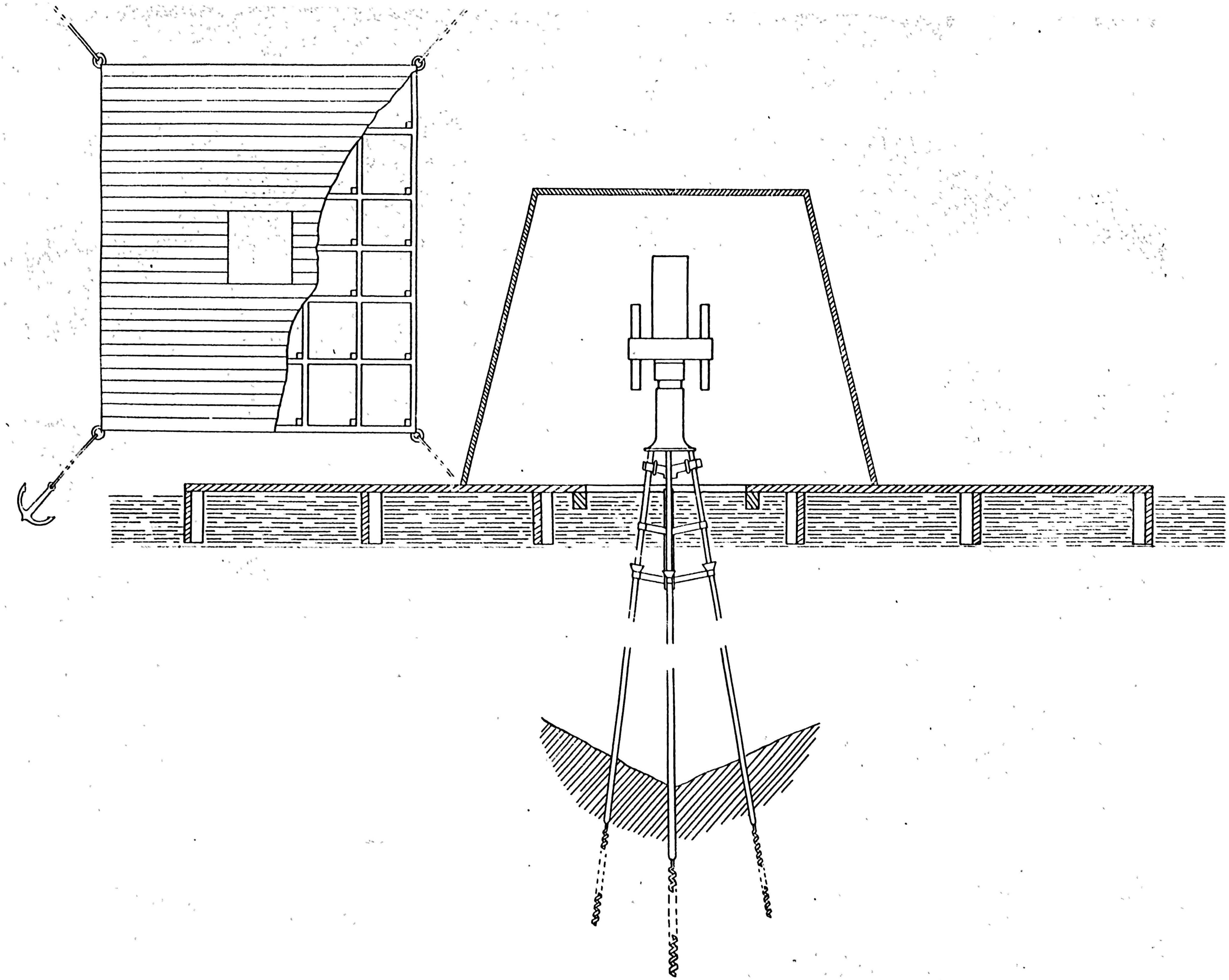

Fig. 3 Drawing showing construction of float used in connection with tripod in making torsion balance surveys of inundated areas.

The first reading period (normally eight hours) was never completed, for the concrete structure shifted during the course of the reading, necessitating the removal of the balance. After numerous attempts to get satisfactory readings had failed, the concrete base approach was abandoned.

It thus became obvious that the original idea of a massive base structure would have to be abandoned. First, the required expenditure of time and money was too great. Second, satisfactory readings could be obtained only in quiet water, inordinately limiting the periods of operation. And, finally, the massive structure presented a hazard to night navigation[4].

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4. As an example of the difficulties encountered by others in attempting to get torsion balance data from inundated areas, we quote from Donald C. Barton, Case Histories, Quantitative Calculations in Gravimetric Prospecting, Petroleum Technology, Nov. 1944, P. 38. "The conditions of observation were the worst that have been encountered on any torsion balance survey under the writer's direction. The depth of the water in the lake averages 4 ft. and reaches a maximum of 8 ft., and 43 of the 57 stations were in the lake. The bottom of the lake is very soft silt and gumbo, the thickness of which increases from nothing at the shore to 20 to 35 ft. in the central area.

The torsion balance was set on a wooden tripod of two-by-fours driven into the mud within a triangular iron cofferdam set on bottom. The instrument shelter was set on a square scaffold supported by four two-by-fours driven into the mud. A wooden baffle was dropped from the house into the water to seal the house from the wind and to shelter the iron cofferdam from waves. Log beams were swung on the three sides into the

Experiments with Tripod Bases:

By the fall of 1932 the experiments with the massive type structures had demonstrated their inadequacy and work with them was abandoned. However, this effort was not all in vain, for certain lessons were learned from these failures which were applied in the later experimental work. The massive structures failed to give the desired stability, partly because they absorbed much of the motion of the water through the ooze on the bottom. The approach then adopted was that of a light but rigid structure which, presenting a minimum surface to the waves, would be firmly secured in the sediments underlying the ooze. These needs seemed to be best filled by the tripod.

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wind and were banked with floating masses of water hyacinth, to break the major force of the waves.

Fully three days of observation was required to get a reasonable set of readings at a few stations, mostly in the central part of the lake. Although the water within the instrument house might seem almost motionless, sufficient vibration was transmitted through the mud to keep the balance system in constant quiver. Usable readings could be taken only during calms or periods of light breezes. During such periods, the quiver of the balance system commonly did not die down completely, but usable readings were obtained by recording the limits of swing for 10 to 20 swings and taking the median position for the desired reading. The method of 180° positions was used; that is, 0°, 180°, 0°, 180°, etc.; and then 90°, 270°, 90°, 270°, and so on. A lull for $2\frac{1}{4}$ hr., therefore, would suffice for a set of readings and check for one component of the gradient. An observer was on duty at the instrument night and day, in order to catch such lulls."

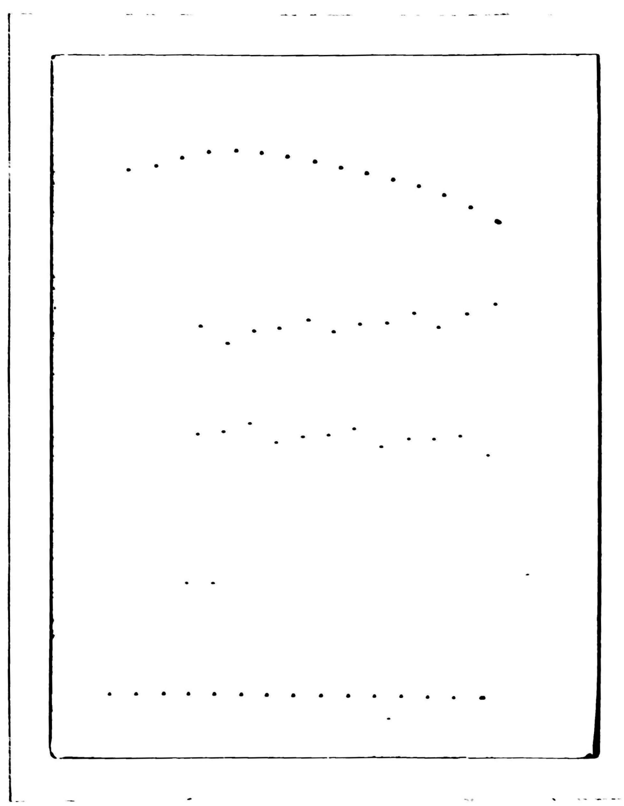

Fig. 4 Torsion balance plate taken over water during a hard storm using tripod and float as finally developed.

Before experimentation could be started on the tripod the political situation in Germany reached a crisis and, as the future of operations by foreign capital in the Reich appeared to be short lived, all experimental work was discontinued. The following summer the concessions were sold and the writer severed his connection with the Sinclair Exploration Company and, with F. J. G. Neumann and W. R. Haubold, moved to Houston, Texas. During the fall of 1933, the writer and his associates started building the first experimental tripod.

Experimental work was started at the mouth of Double Bayou in Galveston Bay. This location was chosen not only because of the current flowing into Galveston Bay at this point, but also because this location was exposed to the full sweep of wave action generated throughout the full length of the bay. A camp was established near this point, materials assembled, and a test tripod was built.

To construct the first tripod, legs made from two inch steel pipe were manually pushed into the clay below the water at an angle of approximately sixty degrees with the horizontal. The upper ends of these legs were fastened together with a single brace of one inch flat iron, forming a base about thirty inches in diameter. The balance was placed upon this structure and a reading was attempted. The first reading was in relatively calm water and the results were acceptable. Readings were then continued on this same structure and location during various degrees of wave action resulting from a wind velocity ranging from five to twenty-five miles per hour. The data were acceptable in wind velocities up to ten miles per hour, but with higher velocities the results were not satisfactory.

According to the U. S. Weather Bureau at Houston, the average wind velocity in this area was approximately fifteen miles per hour[5].

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5. Oral Communication

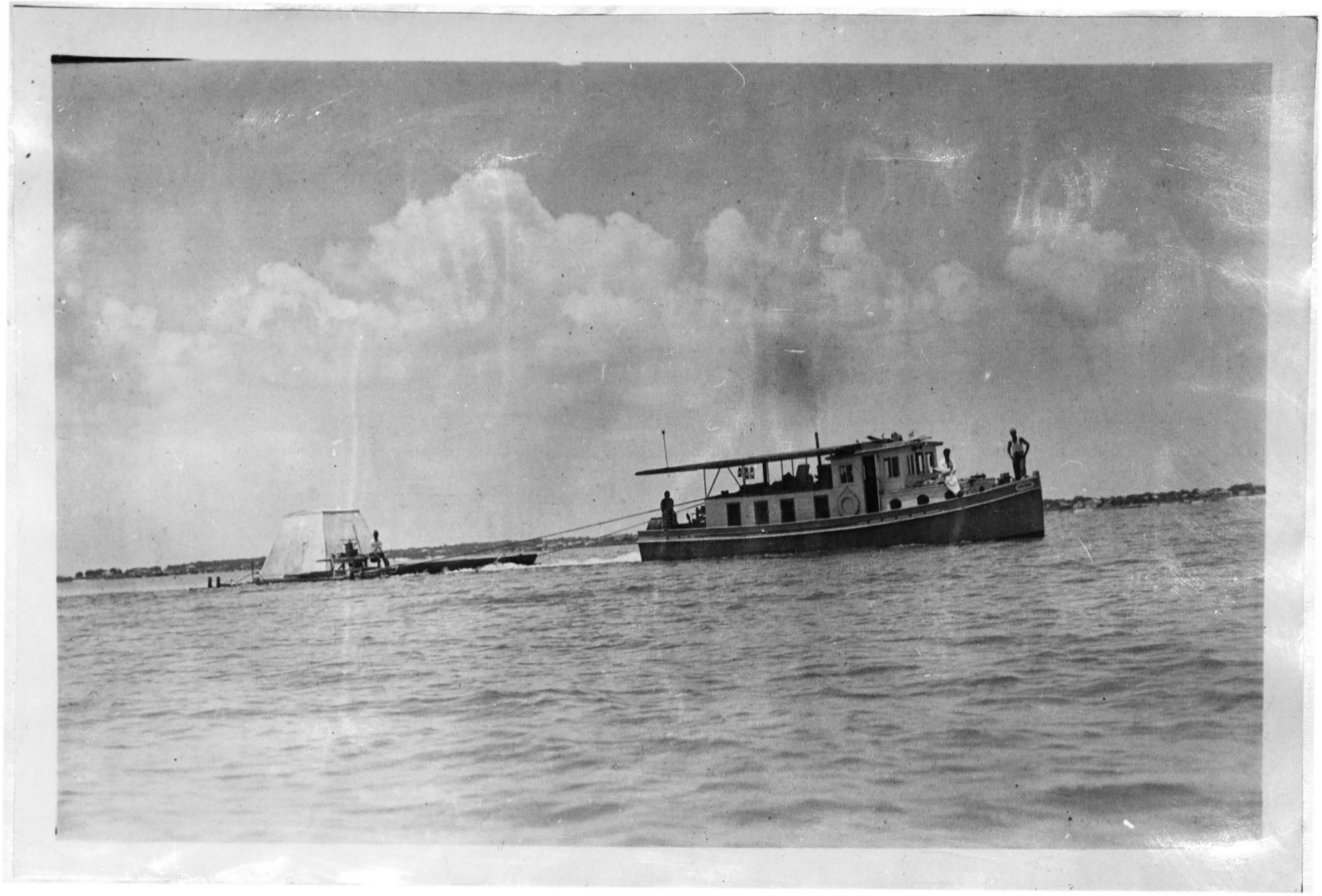

Fig. 5 Power boat towing float to station location.

This condition made it apparent that the tripod would have to be strengthened before it would be practical for this locality.

A study of the structure under various stresses demonstrated two major weaknesses in the tripod. First, it was found that the legs, no matter how firmly they were pushed into the bottom of the bay, did not grip the bottom firmly enough to prevent the tripod from being pushed over with a horizontal thrust. In the second place, the legs of the tripod were so long that they had a tendency to buckle under either a vertical or horizontal thrust.

It was also recognized at this time that, in order to get reliable torsion balance data, some method would have to be devised which would prevent the waves from approaching too close to the instrument. Even though the rigidity of the supporting structure was sufficient to prevent the battering action of the waves from jarring the instrument, still, the gravitational pull due to the mass of waves in close proximity to the instrument was enough to affect the measurements.

A cork screw like coil, approximately three feet in length and about two and a half inches in diameter, made from five-eights inch steel rod, was fastened to the lower end of the legs of the tripod. (See Fig. 2) By means of these coils, the lower ends of the tripod legs were screwed into the bottom of the water body through the ooze and into the underlying compacted sediment. Thereby an improved grip on the bottom was established. When tested, this type of anchorage was found to give much more stable support than did the tripod legs pushed or driven into the bottom.

To stiffen the legs and give greater rigidity, the strap iron, used to bind the legs together, was replaced by a spider consisting of a central hub and three arms, firmly clamped to the ends of the three legs of the tripod. (See Fig.2) A jack screw was carried in this central hub and threaded into the top of a mandrel which hung below the spider. The mandrel carried two sets of arms, the lower of which carried collars, through which the legs of the tripod were passed, while the upper set carried open clevises into which the legs fitted. (See Fig.2) When the jack screw was turned in a direction necessary to force the mandrel down, the collars on the lower arms drew the legs firmly into the clevises on the upper arms, and thus drew the tripod into a rigid structure.

Before making a test of the improved tripod, a square float was built about thirty feet on a side. The frame of this float was constructed from two by twelve inch timbers, and covered with one inch boards to form a deck. (See Fig.3) A square hole about six feet on a side was left in the center of the float, in which to set up the tripod and instrument, and a tent erected over it to protect the balance from the sun and wind.

When these improvements had been completed, the float was anchored in position, the tripod set up, the torsion balance placed therein, and a test run made. The first results were so successful that the test was continued without making any substantial changes in the equipment. While these tests were under way, a hard storm or "norther" blew up, with wind velocities of from thirty five to forty miles per hour. Although this condition was somewhat unusual, the test was continued throughout this storm. The results of this test, which are shown in Fig. 4, indicated that the balances in the instrument would come to a complete rest, even under conditions as unusual as these. As the equipment now had demonstrated its ability to weather storms with twice the average wind velocity for this area, it was obvious that the experimental difficulties had been overcome, and steps then were taken to organize the procedure for the initial gravity survey of an inundated area.

DESCRIPTION OF SURVEY EQUIPMENT

In its completed form the equipment for making torsion balance surveys of inundated areas consisted of three units; the torsion balance (any commercial balance could be used), a tripod on which to place the instrument while a reading was being taken, and a float which not only prevented the waves from striking the tripod, but also carried the necessary personnel and equipment[6]. These were supplemented by a power boat for moving and carrying the equipment (Fig. 5) and which also was used for living quarters for the crew. Skiffs were used for general utility work, such as placing anchors, etc. The necessary surveying was done from a second power boat.

As finally perfected, the tripod consisted of three main units; the legs, the central hub or mandrel, and the upper spider, which connected with the mandrel by means of a jack screw. (Fig. 2) The legs were built of two inch tublar steel made up in joints of various lengths permitting operation in various water depths. The segments of the legs were made up by means of steel tool joints with the same outside diameter as the pipe, that is, about two and three-eighths inches. The lower joint of each leg carried the cork screw-like coil described above.

The mandrel, which experimental work had proven to be an important factor in stiffening and stablizing the tripod, consisted of a central steel core to which two sets of angle iron arms were welded. (Fig. 2) Eachset consisted of three arms spaced 120 degrees apart, the lower set being placed a few inches above the lower end of the mandrel and the upper set being about two and a half feet above the lower set. The upper set of arms were so oriented with the lower set that each arm of the upper set was

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6. See U. S. Patent No. 1983483for detailed description of tripod and float.

parallel with an arm of the lower set. These arms were extended from the central core at an angle of approximately 60 degrees from the vertical as measured from the top of the unit. The lengths of the arms of the two sets were so proportioned as to support the legs of the tripod at an angle of approximately 60 degrees from the horizontal.

Each of the lower set of arms carried a collar slightly larger than the tubing used for tripod legs. This collar was rigidly attached to the arm which carried it, and in a position such that the axis of the collar was in the same plane as the axis of the mandrel and at an angle of about 60 degrees from it, as measured from the top of the structure. The upper edge of each collar was expanded into a funnel-like flange to facilitate the insertation of the tripod legs.

To the outer end of each arm of the upper set, a U-shaped clevis, large enough to receive and support the tripod legs, was rigidly attached. The upper end of the central hub of the mandrel was hollow and threaded to receive a three-quarter inch jack screw.

The upper spider (Fig. 2) consisted of a central hub, to which were welded three angle iron arms about a foot long, radiating from the hub at angles of 120 degrees. At the end of each of these arms, a clamp was attached, by means of a horizontal pin. When the leg of the tripod was being run through the collar on the lower arm of the mandrel, the clamp hinging on this horizontal pin would be folded inward onto the spider arm out of the way. The clamp consisted of two pieces of two inch strap iron, attached to the spider arm by the pin mentioned earlier, and shaped to fit around the end of the tripod leg. The outer ends of these strap iron pieces were held together by a bolt and wing nut, so that the clamp could be quickly and easily attached to or removed from the tripod leg.

The central hub of the spider, (Fig. 2) to which the arms were welded, consisted of a cylindrical steel block about six inches in diameter and about two inches thick. This block had a hole, about four inches in diameter and about one and one-half inches deep, drilled into the top. A three-fourths inch hole, in the center of the cavity thus formed, penetrated the remainder of the block. A flange or collar fitted into this recess and was pinned to the upper end of a three-quarter inch jack screw, between two and three feet long, which hung below the hub. A collar, securely pinned to the shaft of the jack screw just below the hub of the spider, prevented the jack screw from being thrust upward through the hub. Thus, the jack screw was free to turn in the hub of the spider, but could not be moved up or down in relation to the spider. The lower collar on the shaft of the jack screw was about two inches thick, and had a series of equally spaced half inch holes drilled in the side around the collar to receive the end of the rod which was used as a wrench to turn the jack screw.

To assemble the tripod, the jack screw on the spider was first run about two thirds its length into the upper threaded end of the mandrel, and the two units suspended over the location to be occupied with the mandrel hanging down. These units were suspended either by means of cross beams under the arms of the spider or by ropes from beams above. The clamps on the ends of the spider were folded in on top of the arms of the spider, and the legs of the tripod started through the collars on the lower arms of the mandrel. The joints, of which the legs were composed, were assembled as the legs were lowered. When the coils on the lower ends of the legs reached the bottom of the water body, the legs were turned, either by hand or with a pipe wrench depending upon how much resistance was encountered, (Fig. 6) until the legs had been drawn into the bottom sediments deep

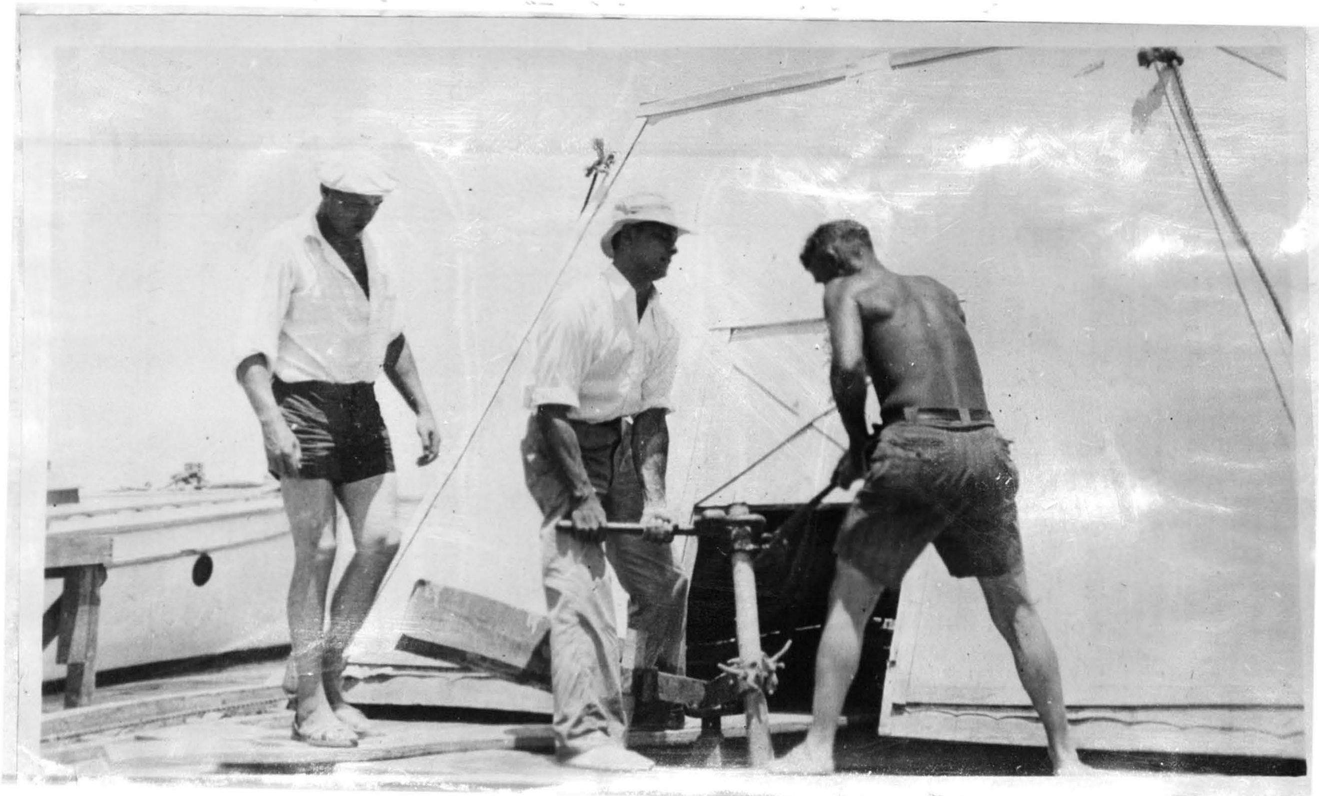

Fig. 6. Turning the tripod leg into the bottom. Note the small door in the side of the tent which will permit the tent to be moved over the assembled tripod.

enough to secure a firm anchorage. After all three legs of the tripod were firmly in place with the tops approximately level, (Fig. 7) the clamps on the ends of the spider arms were fitted onto and tightly clamped to the upper ends of the legs and the support for the spider and mandrel removed. The jack screw then was turned in the direction necessary to force the mandrel down. This drew the legs of the tripod inward toward the axis of the structure, and firmly into the clevises on the upper arms of the mandrel, taking up any slack in the structure and forming it into a rigid unit.

The float, which was described briefly above, was a very important part of the equipment, as it simultaneously served several purposes. It was first a platform for operations, a place for the men to stand while setting up and dismantling the tripod and balance. It prevented the waves from coming against the instrument or tripod, and thus protected them from shock, and at the same time kept the waves far enough away from the balance to prevent their mass from deflecting the instrument. Finally the float supported the tent used to shield the balance from sun, wind and spray.

As was mentioned above, the float was about thirty feet square. The frame was formed from 2" x 12" timbers, or beams, set on edge and cross-braced with similar material. (Fig. 3) Tie pieces across the ends held the beams together. A deck of one inch boards was laid upon this frame for a working platform. A hole about six feet square was formed in the center of the float, through which the tripod was set up. In the construction of this float, no iron or steel was used which could be avoided. Wherever possible joints were made by means of dowels, and where nails or bolts or other iron fixtures were unavoidable they were either placed in pairs symmetrical to the center of the float, or where counter-balanced on the float by objects of equal mass. This was done in order that the center of gravity of the float, as a whole, would be at its center, and

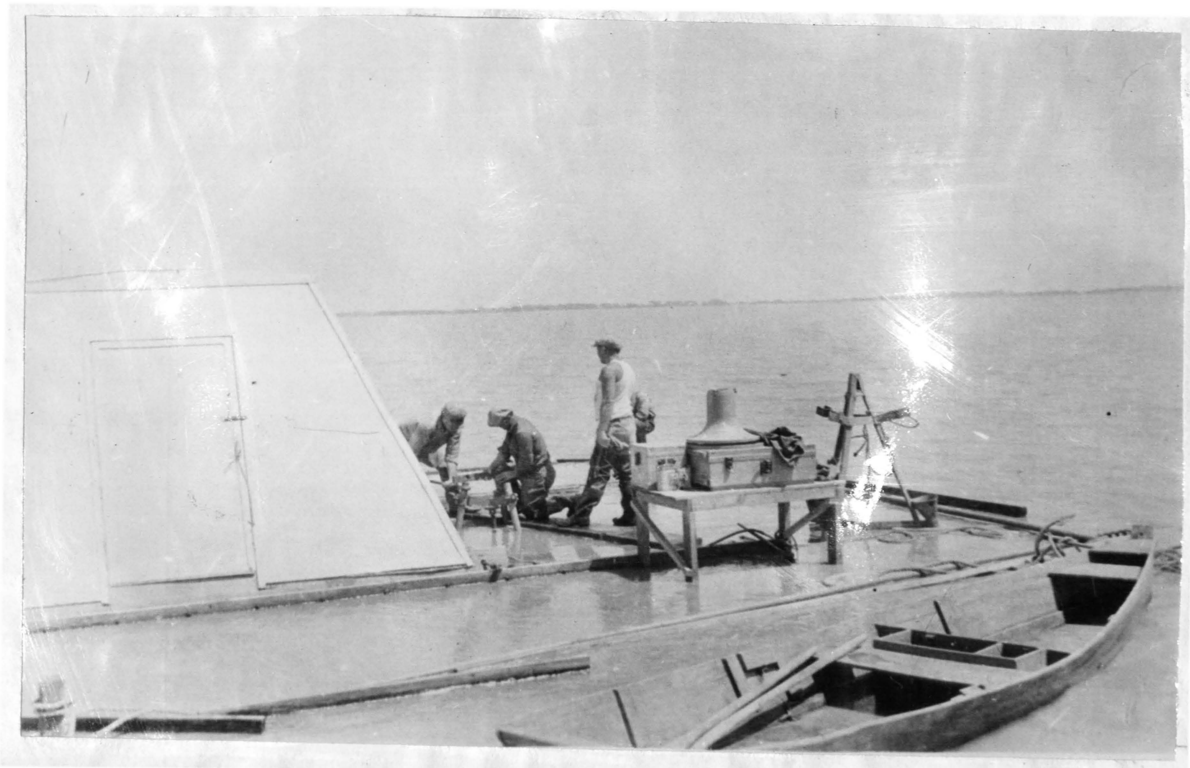

Fig. 7. Leveling the tops of the tripod legs. Note door in side of tent.

would not affect the validity of the measurements of gravity by the balance.

The tent, which shielded the instrument, (Fig. 3) was built on a rigid frame and mounted on small rollers, or wheels. These fitten on a light track on each side of the central opening, so that the tent could be rolled to one side while the tripod was being erected. A low opening in the side of the tent, closed at other times by a sliding door, (Fig. 6) permitted the tent to be rolled into position after the tripod was in place. A full sized door on another side of the tent (Fig. 7) gave access to the tent for mounting, dismounting or otherwise servicing the instrument.

Besides the torsion balance, tripod and the float, boats were needed to expidite the survey procedure. A fifty-nine foot tug boat, with a twelve foot beam, was used to move the float (Fig. 5) and was equipped with sleeping accomodations for eight men and complete galley for feeding the crew. Storage space for the tripod, torsion balance and computation and drafting equipment was also provided. A small power boat was used for surveying in the locations. (Fig. 8) Two skiffs used for general utility work completed the equipment.

PATENT POSITION

When the tripod and float had been completely developed and reduced to practice it was decided that it constituted an invention, and Newell, Spencer and Safford, patent attorneys of New York City, were employed to secure a patent. On December 4, 1934, Patent No. 1983483, in which fifteen claims were made, was granted to F. J. G. Neumann and W. R. Haubold and assigned to The Salt Dome Oil Corporation of Houston, Texas.

Fig. 8. The small power boat used for surveying in stations.

SURVEY PROCEDURE

After the necessary equipment had been assembled, plans for the making of torsion balance surveys of inundated areas were put in operation. It was decided, after having made a study of the geology of several inundated areas, to begin actual survey operations on Galveston Bay. The actual surveying may be reduced to four fundamental operations, namely, the location of the stations to be occupied, the actual occupation of the station, moving to the new location, and the computation of the data obtained and plotting it on a map.

The location of the stations was made with a small power boat. (Fig. 8) A predetermined line was established across some part of the bay. In order to have as accurate a map as possible of the bay area for the establishment of these lines, aerial photographs were used. When the line had been established by markers, the power boat was run along the line and the stations located by means of two by two inch sticks long enough to extend above the water level when pushed into the bottom of the bay. These were marked with flags. The spacing of the stations was determined by running the power boat at a constant speed, determined by a tachometer, for a given length of time. The alignment of the stations was made by sighting on the established markers.

After the stations had been staked out, the precise location of each was determined by triangulation from established points either along the shore or on towers established out in the water. If angulation showed that the desired coverage and survey density would not result, individual stations were relocated.

When the stations to be taken had been located, the float was towed into position on the first station to be occupied, and securely anchored.

Four anchors were used, one for each corner, and these were placed, by means of skiffs, as far as was practical from the float in order to get as large a horizontal component on the anchor rope as possible. When all four anchors were in position, the ropes were drawn taut so that the float would have a minimum of horizontal movement. Then the tripod was erected in the opening in the center of the float, the tent rolled into position, (Fig. 9) and the balance erected on the tripod. (Fig. 10) When the balance had been leveled and oriented (by means of a compass), a photographic plate was inserted and the clock and stops properly set. Finally, all tools and loose equipment were removed to the tug boat and the entire crew, left the location for the normal eight hours "reading period".

Soundings of the bottom of the bay around the station were taken from the skiffs, to determine if irregularities were present, and, if so, their size and location. In only a few places were any found requiring terrain corrections.

At the end of the normal reading time, the boat returned to the float, the stops on the balance were locked in place, the plate extracted and the balance removed. The tripod then was dismantled, the anchors hauled in and the float towed to the new location. While the float was being moved to the next station, the observer would develop the photographic plate in a small dark room on the tug boat.

The entire equipment could be dismantled, towed to the new location, and the station completely occupied, with the instrument in position, in about an hour and a half, except in cases of long moves or other unusual situations. Therefore, each party was equipped with two torsion balances, tripods and floats. The operations were so organized that one instrument would be moved while the other instrument was in position.

Fig. 9. The tripod in place ready to receive the torsion balance. The tent has been drawn into position over the central opening of the float.

The data was computed by the usual method, which has been adequately described in the literature[7]. In one respect, the computations were simpler than those used in land surveys, for in only a few cases was it found necessary to make terrian correction.

LIMITATIONS OF APPARATUS

The equipment, for making torsion balance surveys of inundated areas, as described above, was found to have limitations based upon the water depth and the nature of the bottom. For instance, the construction of the tripod was such that it could not be used in less than about four or five feet of water unless the mandrel, which is nearly five feet long, was left off. As the tug boat used to tow the float drew about four feet of water, no attempts were made to carry the work into areas of less than that depth. However, by using a smaller boat and a shorter mandrel, there is no reason why the work could not be carried into relatively shallow water.

Deep water presented a different problem. Experience demonstrated that about fifty feet of water was as great a depth as the equipment described here, could be relied upon. In the deeper water, the legs of the tripod extended so far below the mandrel that a buckling tended to develop. However, it is the writer's opinion that, by using a larger float, heavier legs on the tripod and a longer and heavier mandrel, surveys can be made in waters of even greater depths than those encountered to date.

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7. Barton, Heiland, Lancaster-Jones, Jakosky, Nettleton and others.

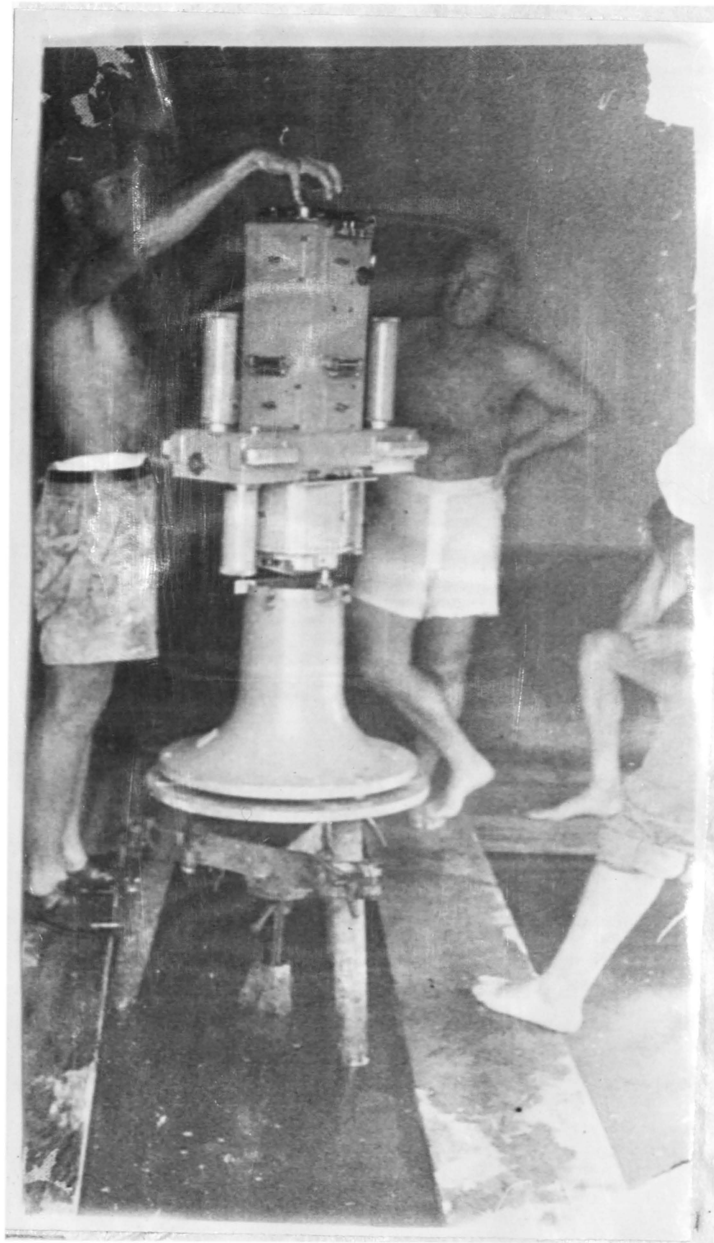

Fig. 10. The torsion balance in place upon the tripod.

The other type of limitation, that imposed by the nature of the bottom, was as follows. In one part of Galveston Bay, the bottom ooze was so thick that the legs of the tripod, even when extended to sixty feet, were unable to penetrate it and reach the firm sediments necessary to give the tripod stability. The maximum thickness of this ooze was never determined. It may be that by using longer and heavier legs, supported by a heavier mandrel, this ooze could be penetrated and a firm bottom found. At the present writing, however, no method exists for making torsion balance surveys of inundated areas where the water bottoms are characterized by these waterial thicknesses of ooze.

COST OF OPERATION

For two reasons, the cost of making torsion balance surveys of inundated areas is, on the average, greater than surveys of similar density on land. Boat operation is not only more expensive than truck operation, but also requires a numerically greater personnel. A direct comparison of costs follows: In 1934, The Salt Dome Oil Corporation maintained a water crew in operation on Galveston Bay and a land party working in the immediately surrounding area. The crews had two instruments each and were obtaining approximately the same number of stations per month. The total cost to the company for these two parties was about $2,660.00 per month. Of this, the water crew cost about $1,625.00, and the land crew about $1,035.00. Thus, at that time the water crew cost, on the average, about 57 percent more than did comparable land operations.

RESULTS OF SURVEYS OF INUNDATED AREAS

Fairly complete reconnaissance surveys and some localized detail surveys were made in Galveston Bay in Texas and Barataria Bay in Louisiana.

In Galveston Bay, eight major and several minor gravitational anomalies were discovered. In Barataria Bay three outstanding anomalies were found.

All of the eight anomalies on Galveston Bay were detailed with the reflection seismograph. Definite evidence of structure was found associated with seven of them, with some indefinite evidence of structure on the eighth. Six of the anomalies have been tested with the drill. Production has been established on four of these, Cedar Point, Fishers Reef, Smith Point and Double Bayou. On the other two anomalies, four dry holes have been drilled at Marsh Point and two at Elm Grove without establishing commercial production. At both prospects, the upper sands were poorly developed and, because of heaving shale, the Frio section was not reached by the drill and so these two prospects present as yet untested possibilities. After the anomalies were discovered on Barataria Bay leases could not be secured, and so no detail reflection seismograph surveys were made.

The first anomaly found (which was completely in an inundated area) was near Cedar Point in Galveston Bay. Plate I is a gradient and curvature map of this anomaly. Plate II shows the gravity contours, as drawn by Dr. F. J. G. Neumann and superimposed upon the gradients. The torsion balance work which located this anomaly was merely reconnaissance coverage, and therefore it was felt that, before drilling was inaugurated, a check should be made by some other exploration technique. A reflection seismograph party was moved into the area, and the area was detailed by that method. Plate III shows the results of the seismograph detail as contoured by Joseph M. Wilson, superimposed upon the torsion balance data. It is at once apparent that the top of the structure, as shown by the seismograph, lies about 5500 feet slightly north of east of the center of the gravity anomaly.

After the Cedar Point anomaly had been checked by the reflection seismograph, a test well was located, and on February 12, 1938, The Salt Dome Oil Corporation-Standard Oil Company of Texas, #118-1 State, in the north corner of section 118, was completed as an oil well. Since then twenty-five wells have been drilled in this field, of which eighteen are productive. Approximately 640 acres have been proven productive to date. Saturated sands were found scattered through the section, ranging in depth from about 3000 to 6000 feet. Production has been established in three of these sands, two in the Miocene and one in the Frio. The ultimate recovery of the field is estimated at 32,000,000 barrels.

Plate IV shows the structure of the Cedar Point Field, as contoured by D. J. White, Jr., on the top of the Frio sands, superimposed upon the gravational data. As in the case of the reflection seismograph anomaly, the top of the subsurface structure lies to the east of the center of the anomaly.

The gravity anomaly has the characteristics of a deep seated salt dome. The subsurface structure, as interpreted from the logs of the wells in the field, is considerably faulted, and has a graben along the axis of the structure, such as is commonly found over salt dome structures.

RELATIVE DEPENDABILITY OF SURVEYS OF INUNDATED AREAS

The question naturally arises as to whether torsion balance surveys made by the above described method are as dependable a measurement of the variations in the gravitational field as are similar surveys on hand. The only way this question could be definately answered would be by making a survey over a water covered area, and then removing the water and repeating the survey, using the same station positions. This, of course, is impractical.

However, an indirect approach may be made to the problem. One criterion of the relative merit of water and land surveys is whether the water taken data can be tied into and used with land surveys without adjustment or correction. The writer supervised the survey of Galveston Bay, covering approximately 300,000 acres, and a land area of similar size, surrounding and adjacent to it. In the exploitation of these data, at no place was it found necessary to make any correction or adjustment of the values taken over the bay, nor did any discrepancy in the expression of the gravitational anomalies occur along the shore line where the two surveys joined. Due to company policy, the map showing the complete survey of Galveston Bay and the adjacent land area cannot be released at this time. However, Plate V shows parallel land and water taken lines with profiles of the computed gravity values for comparison.

One of the greatest sources of error in torsion balance surveying is the terrain correction made to compensate for irregularities in the surface in the vicinity of the balance. In the vast majority of the stations taken in Galveston Bay and Barataria Bay, soundings made around the instrument indicated that there were no irregularities in the bottom which would have a gravitational effect sufficient to deflect the instrumer This followed not only because the bottom of the bay was very smooth, but also because the difference between the specific gravity of water and those of the bottom sediments of the bay were much less than those between the surface soil and air. Therefore, an irregularity of a given size on the bottom of the bay would have a much less effect on the instrument than would an irregularity of the same size on land.

This view has been borne out by the writer's experience. In his work with the torsion balance in Northern Germany and on the Gulf Coast, the writer has found that often, in spite of the most careful measurements of the terrain, erratic values periodically occur. In working on glacial deposits in Northern Germany, these erratic values were commonly found to be due to local accumulations of gravel. Similar local gravel deposits, though of a different origin, occasionally were found on the Gulf Coast. These accumulations were often so completely concealed that they were found only by digging or shallow coring around a station which gave an erratic or unusual value. Other gravel deposits, small enough or far enough away from the instrument to give only a slight effect, must have modified to some extent the data from many of the other stations.

In the torsion balance surveys of water covered areas made by the writer no such irregularities were found. In all the work done except that around Red Fish Reef, the bottom was found to be so flat and featureless that no terrain corrections whatsoever were needed. In that local area, great holes had been dug in the bottom of the bay by dredges digging up oyster shells. These had to be carefully sounded and correction made for them in gravity data taken near by.

RELATIVE SPEED OF SURVEYS OF INUNDATED AREAS

Reference has already been made to the fact that a water crew, working on Galveston Bay, occupied as many stations per month as did a land crew working the area around Galveston Bay. This was true because a considerable portion of the land adjacent to Galveston Bay consisted of swamps and marshes, which made the work slower than normal. Under these conditions, each crew was able to occupy, on the average, two stations per instrument per working day.

Where the terrain is favorable, the average land crew can occupy three stations per instrument per working day. The work on water is, of necessity, slower than this because of the time consumed in pulling in and placing the anchors and in dismantling and erecting the tripod, and also to the fact that a boat towing the float moves only about one-sixth as fast as does a truck moving over good terrain. The time necessary to erect the instrument, take the reading, and dismantle the instrument is the same on water as on land.

VALUE TO THE OIL INDUSTRY

This technique is not limited to the torsion balance, but also could be used with either the pendulum or gravimeter. As has been pointed out above, at least four fields have been discovered as a result of gravity surveys, using the technique described above. The use made of the torsion balance with this method was that of a reconnaissance instrument, and it is in this respect that gravity instruments could be used most effectively over water by the oil industry. It is not intended here to preclude the use of gravity instruments for detail surveys. In several instances, detail gravity surveys made contemporaneously with other surveys, have given the most reliable delineation of the structure.

The main contribution of this techniquesis that it opens to oil exploration with gravity instruments, water covered areas. In the Gulf Coast Area, including Texas, Louisiana, Alabama, Georgia and Florida, in California, Venezula, the Persian Gulf Area, Russia, and in various parts of the East Indian Archipelago there are vast inundated areas which are potential oil land. By use of this technique or adaptations thereof, these inundated areas can be explored by gravitational and allied methods.

SUMMARY

Field operations in regions where inundated areas existed demonstrated a need for a method exploring these and similar areas. After considerable experimental work, a tripod and float were designed and constructed which made torsion balance surveys of these areas possible. Extensive torsion balance surveys of Galveston Bay in Texas and Barataria Bay in Louisiana led to the discovery of several oil fields. The method makes possible gravity exploration in inundated areas throughout the world.

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